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(45) **Date of Patent: May 24, 2016**

(54) **OPTICAL SYSTEMS AND METHODS EMPLOYING A POLARIMETRIC OPTICAL FILTER**

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(51) **Int. Cl.**

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G01J 3/51	(2006.01)
G01J 11/00	(2006.01)
G01J 3/02	(2006.01)

(52) **U.S. Cl.**

CPC ***G01J 4/04*** (2013.01); ***G01J 3/2823*** (2013.01); *G01J 3/0224* (2013.01); *G01J 3/51* (2013.01); *G01J 11/00* (2013.01); *G01J 2003/2826* (2013.01)

(58) **Field of Classification Search**

CPC G01J 3/2846; G01J 3/51; G01J 3/447; G01J 11/00; G01J 3/0224; G01J 3/2823; G01J 4/04

See application file for complete search history.

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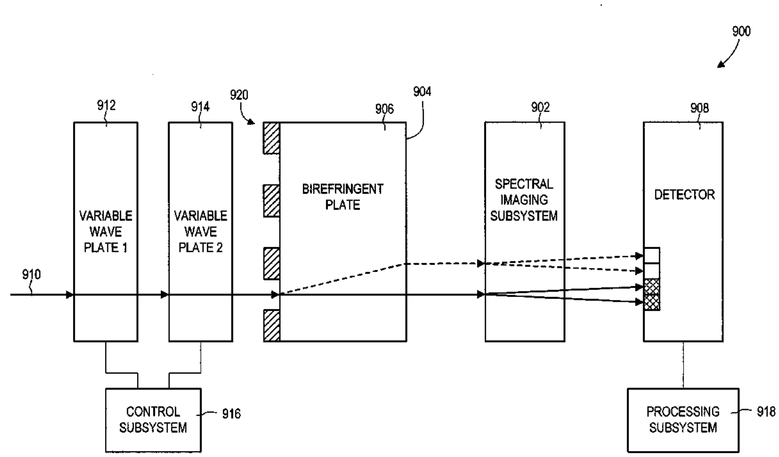
(57) **ABSTRACT**

A birefringent filter includes an EM directing element in optical alignment with a first surface of the birefringent plate. A polarimetric imager includes a birefringent filter including a birefringent plate formed of a birefringent material and an EM directing element in optical alignment with a first surface of the birefringent plate. The imager further includes a detector in optical alignment with a second surface of the birefringent plate. A projection system includes an EM directing element and a birefringent filter. The filter includes (1) a birefringent plate formed of a birefringent material and having a first surface in optical alignment with the emissions source, and (2) an EM directing element in optical alignment with a second surface of the birefringent plate.

21 Claims, 12 Drawing Sheets



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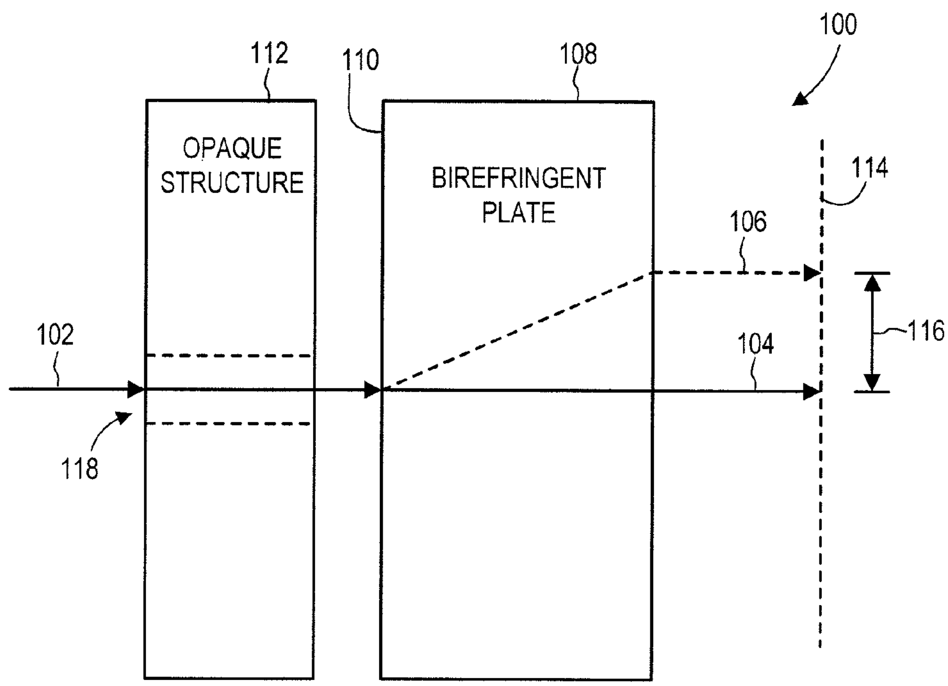
100
112
110
108
OPAQUE STRUCTURE
BIREFRINGENT PLATE
114
106
116
102
104
118

FIG. 1

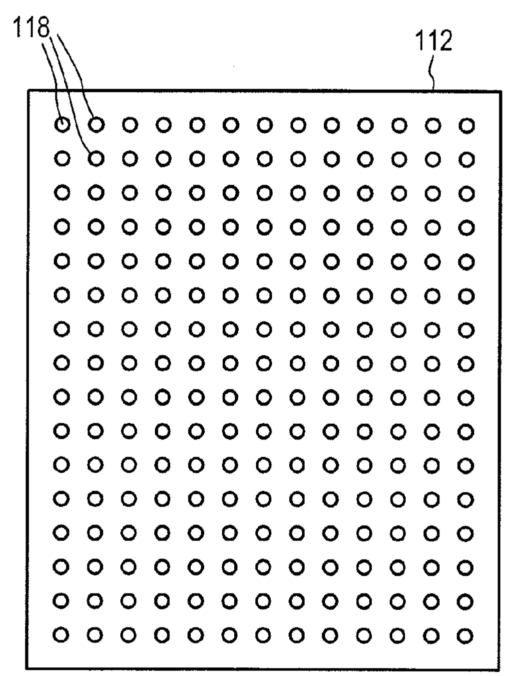
118
112

FIG. 1A

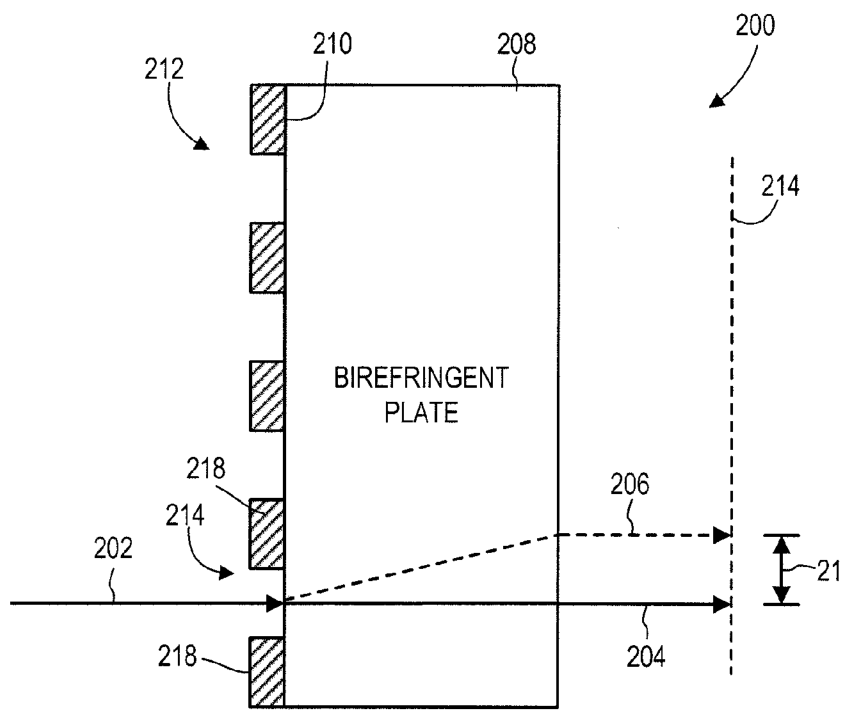
200
212
210
208
214
BIREFRINGENT
PLATE
218
214
206
202
216
218
204

FIG. 2

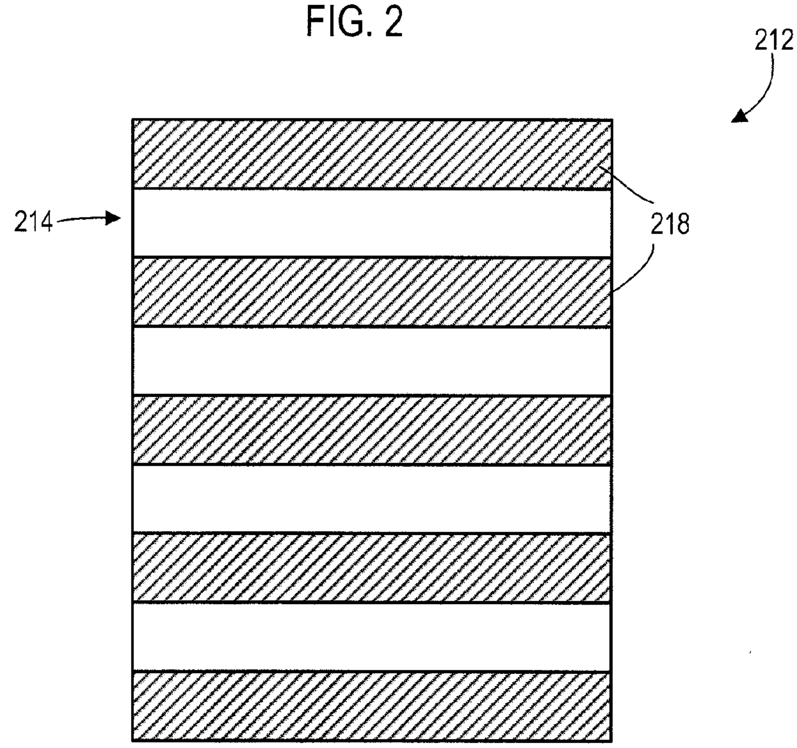
212
214
218

FIG. 2A

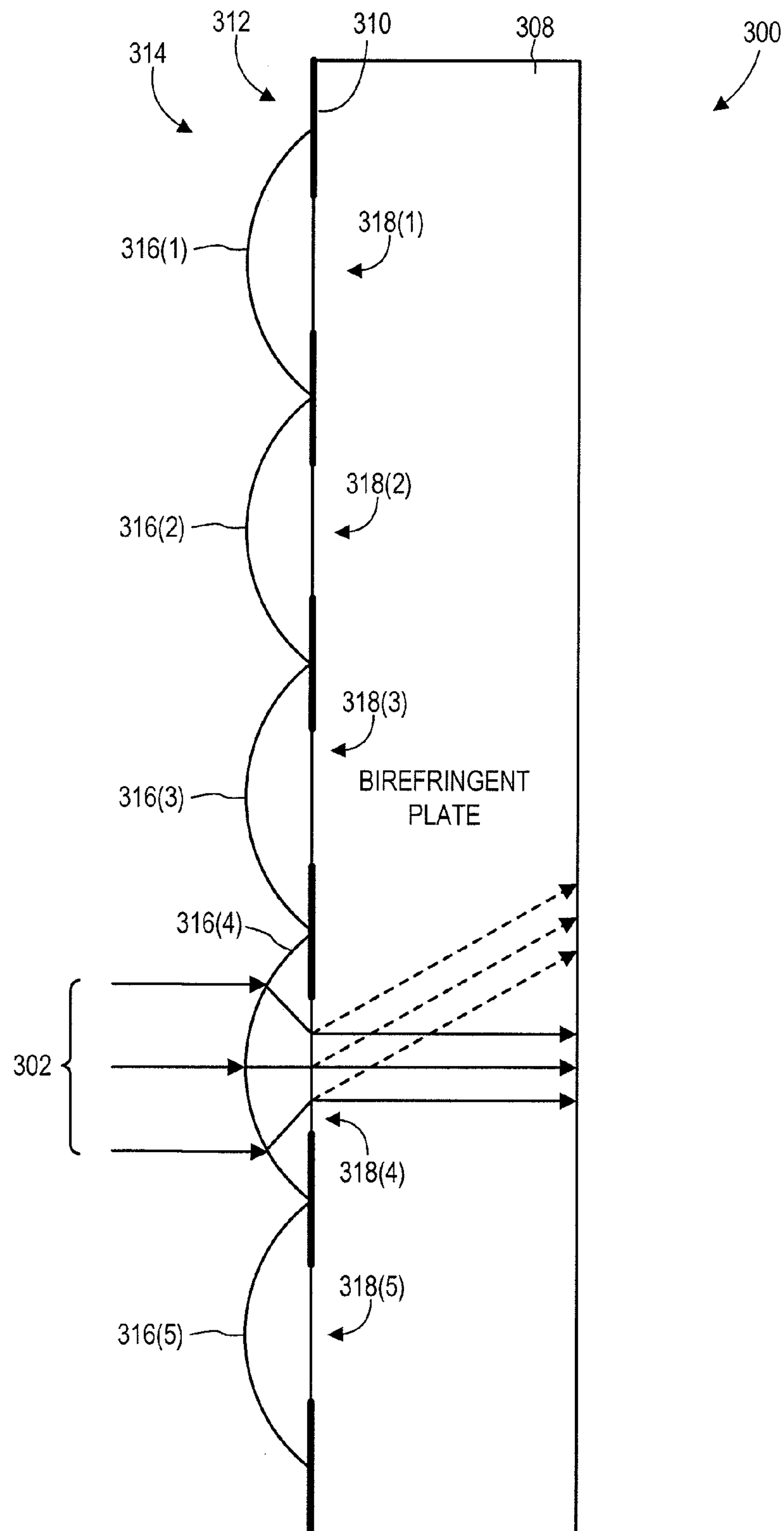
314
312
310
308
300
316(1)
318(1)
316(2)
318(2)
318(3)
316(3)
BIREFRINGENT PLATE
316(4)
302
318(4)
318(5)
316(5)

FIG. 3

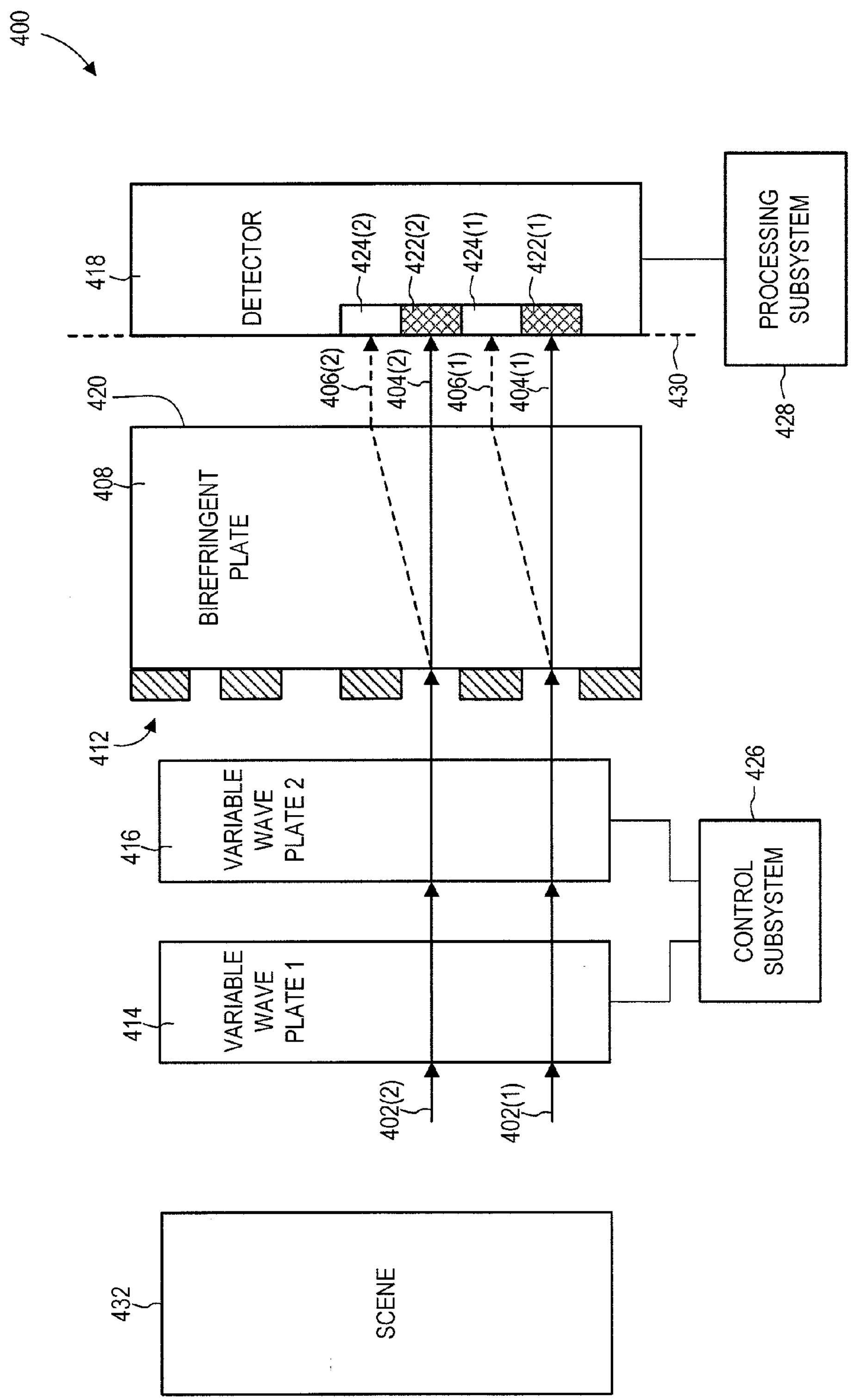
400
418
DETECTOR
424(2)
422(2)
424(1)
422(1)
PROCESSING SUBSYSTEM
428
430
420
406(2)
404(2)
406(1)
404(1)
408
BIREFRINGENT PLATE
412
416
VARIABLE WAVE PLATE 2
426
CONTROL SUBSYSTEM
414
VARIABLE WAVE PLATE 1
402(2)
402(1)
432
SCENE

FIG. 4

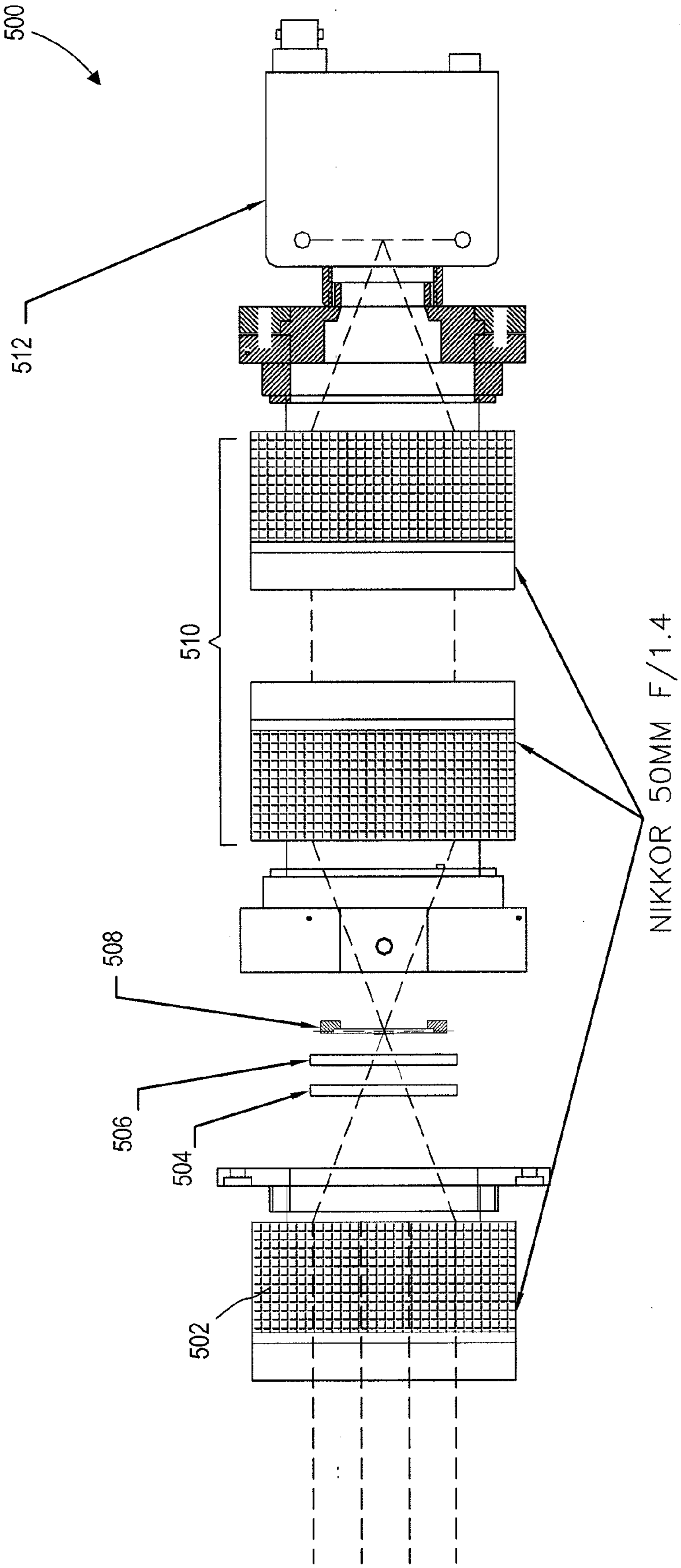

FIG. 5

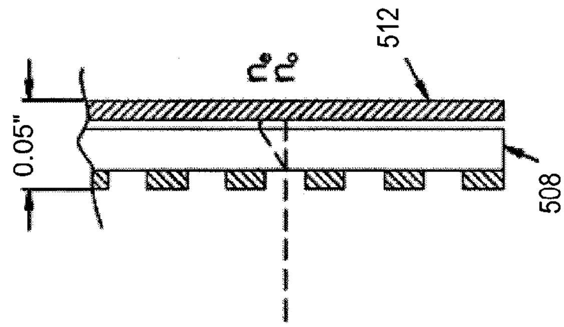

FIG. 8

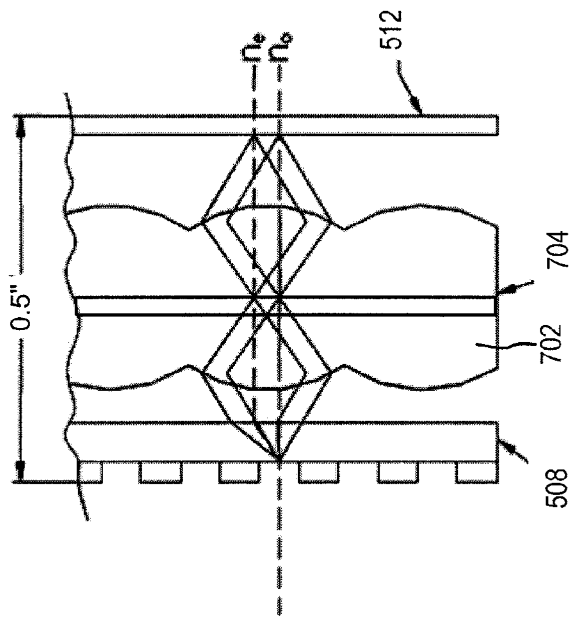

FIG. 7

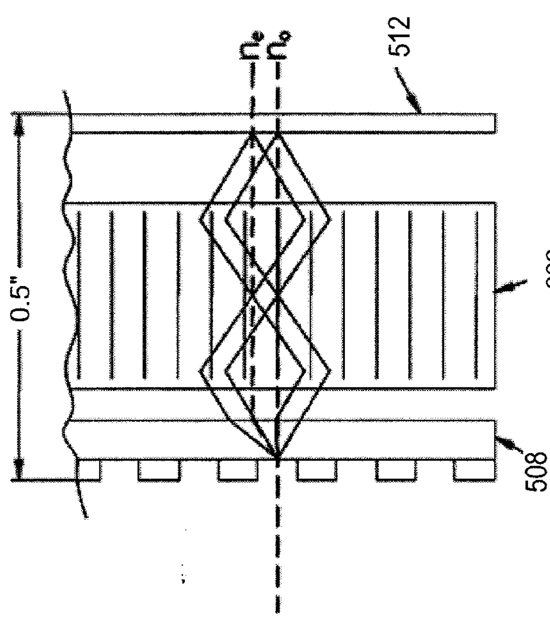

FIG. 6

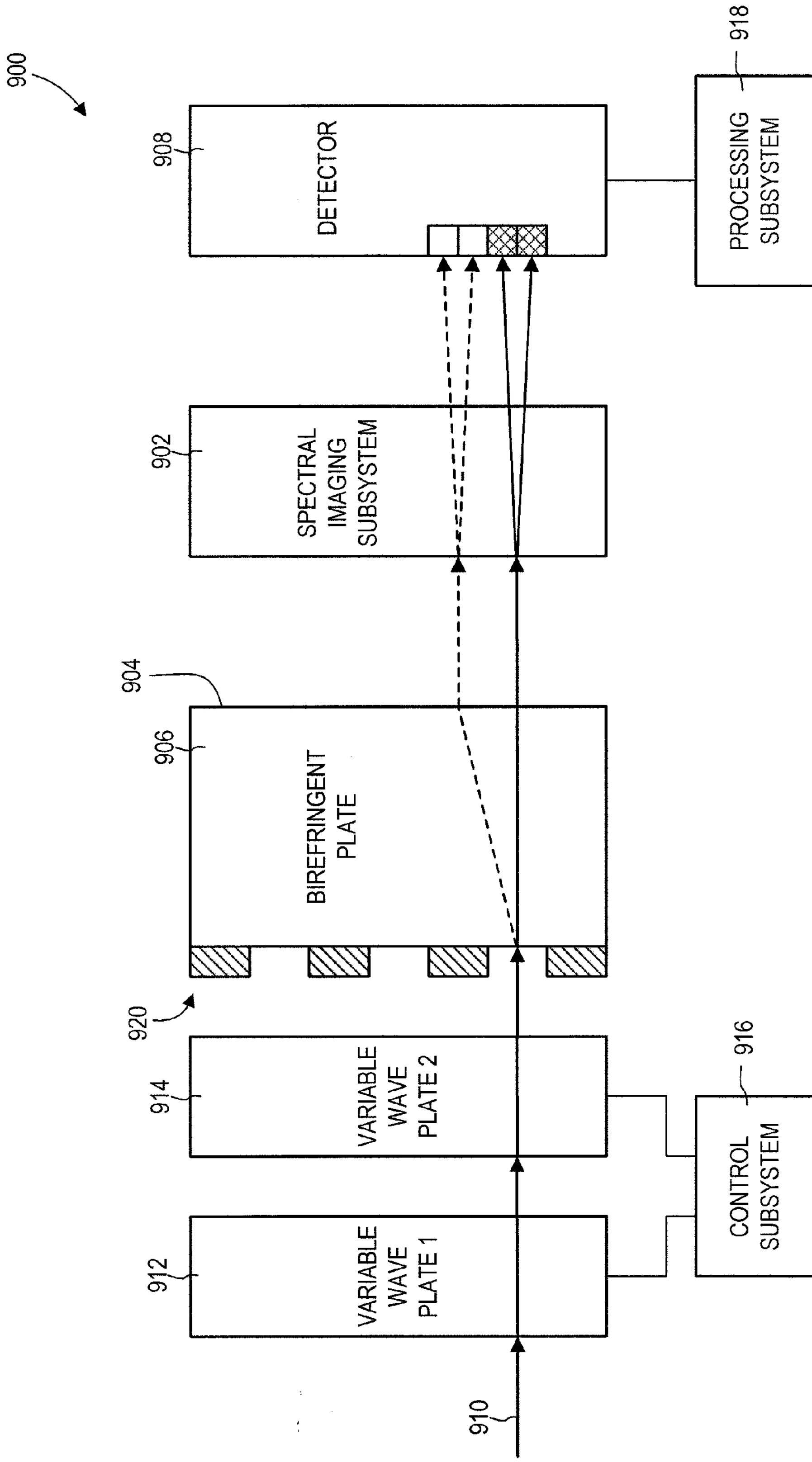
900
908
DETECTOR
918
PROCESSING SUBSYSTEM
902
SPECTRAL IMAGING SUBSYSTEM
904
906
BIREFRINGENT PLATE
920
914
VARIABLE WAVE PLATE 2
916
CONTROL SUBSYSTEM
912
VARIABLE WAVE PLATE 1
910

FIG. 9

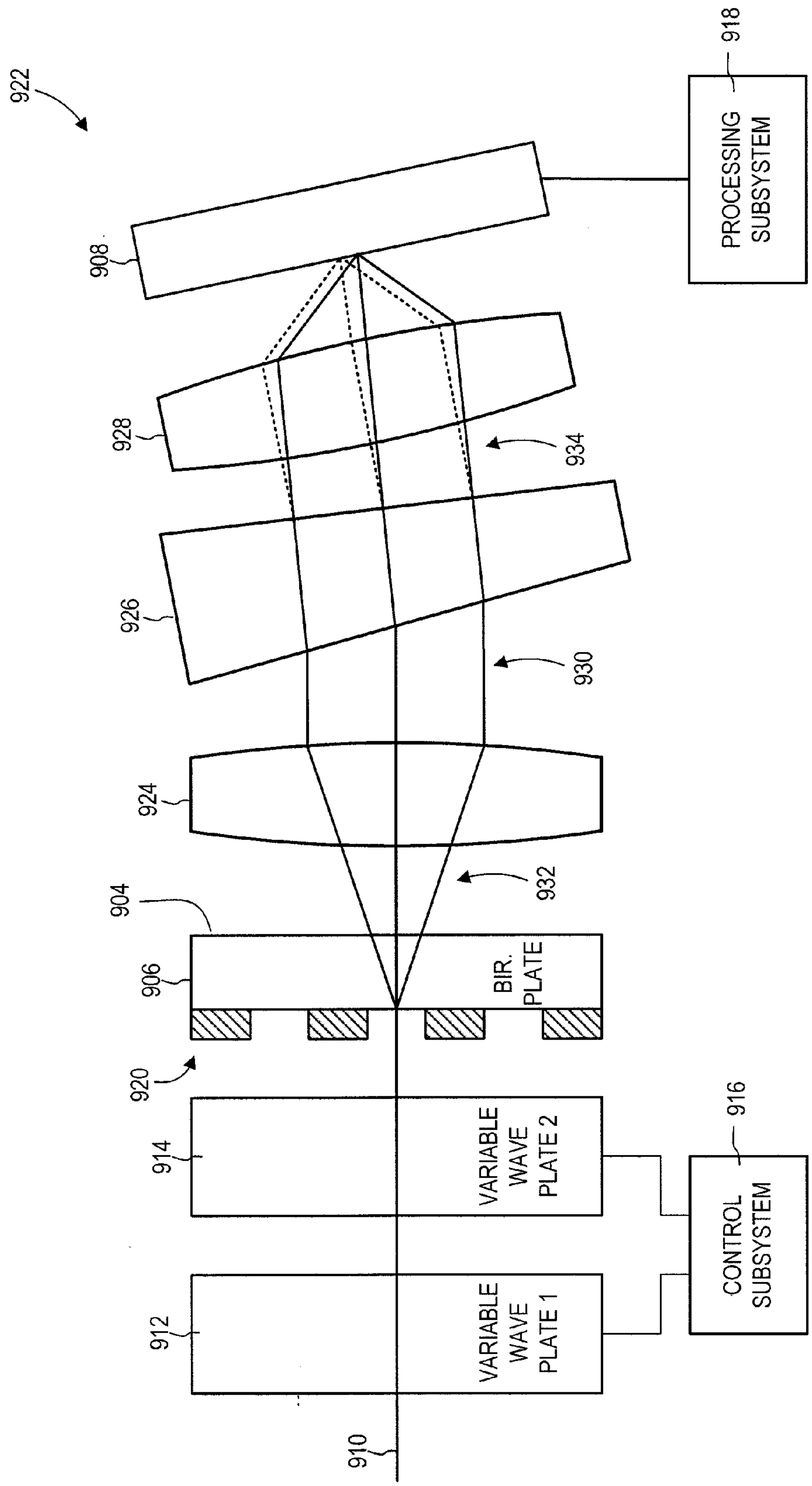
922
918
PROCESSING SUBSYSTEM
908
928
934
926
930
924
932
904
906
BIR. PLATE
920
914
VARIABLE WAVE PLATE 2
916
CONTROL SUBSYSTEM
912
VARIABLE WAVE PLATE 1
910

FIG. 9A

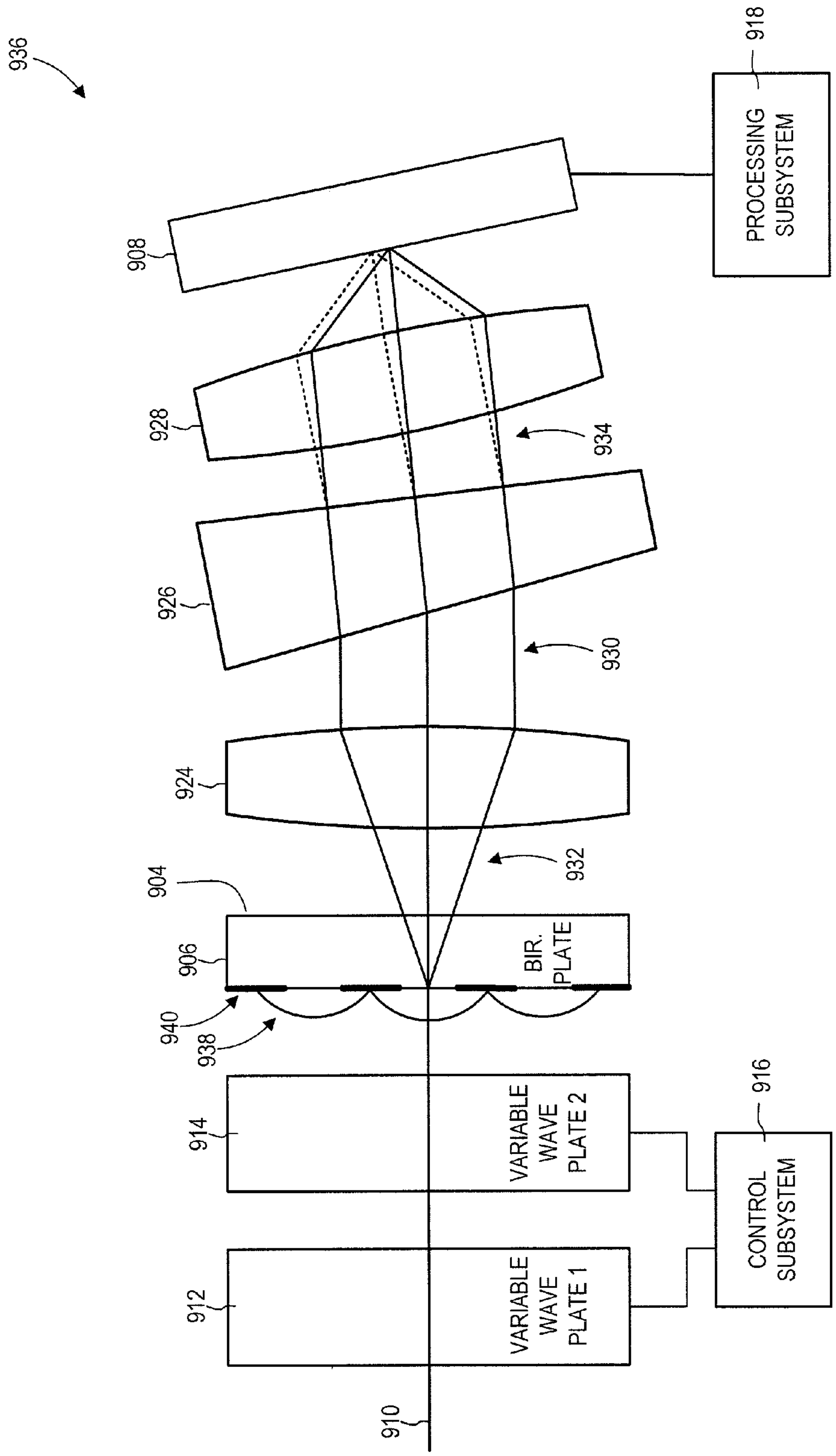
936
918
PROCESSING SUBSYSTEM
908
928
934
926
930
924
932
904
906
BIR. PLATE
940
938
916
914
VARIABLE WAVE PLATE 2
CONTROL SUBSYSTEM
912
VARIABLE WAVE PLATE 1
910

FIG. 9B

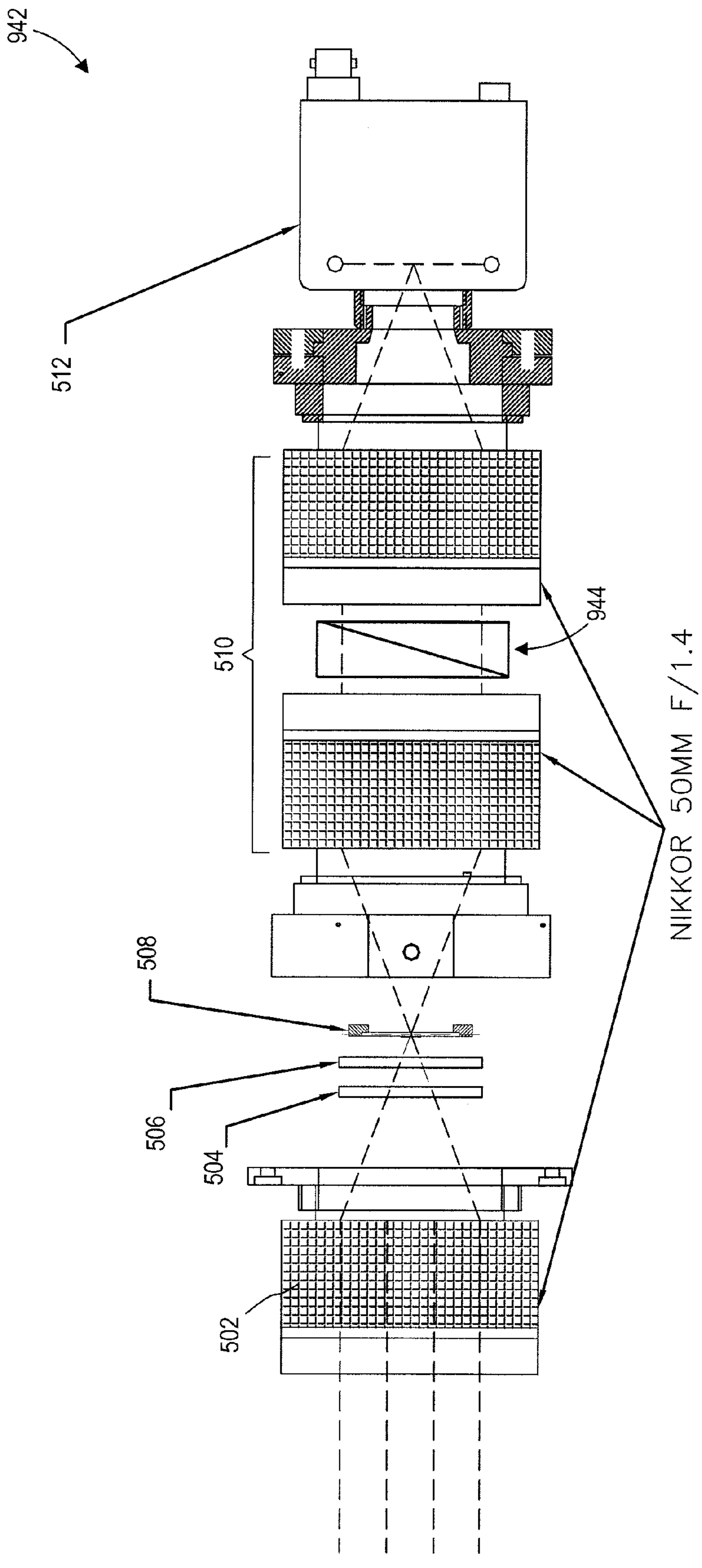

FIG. 9C

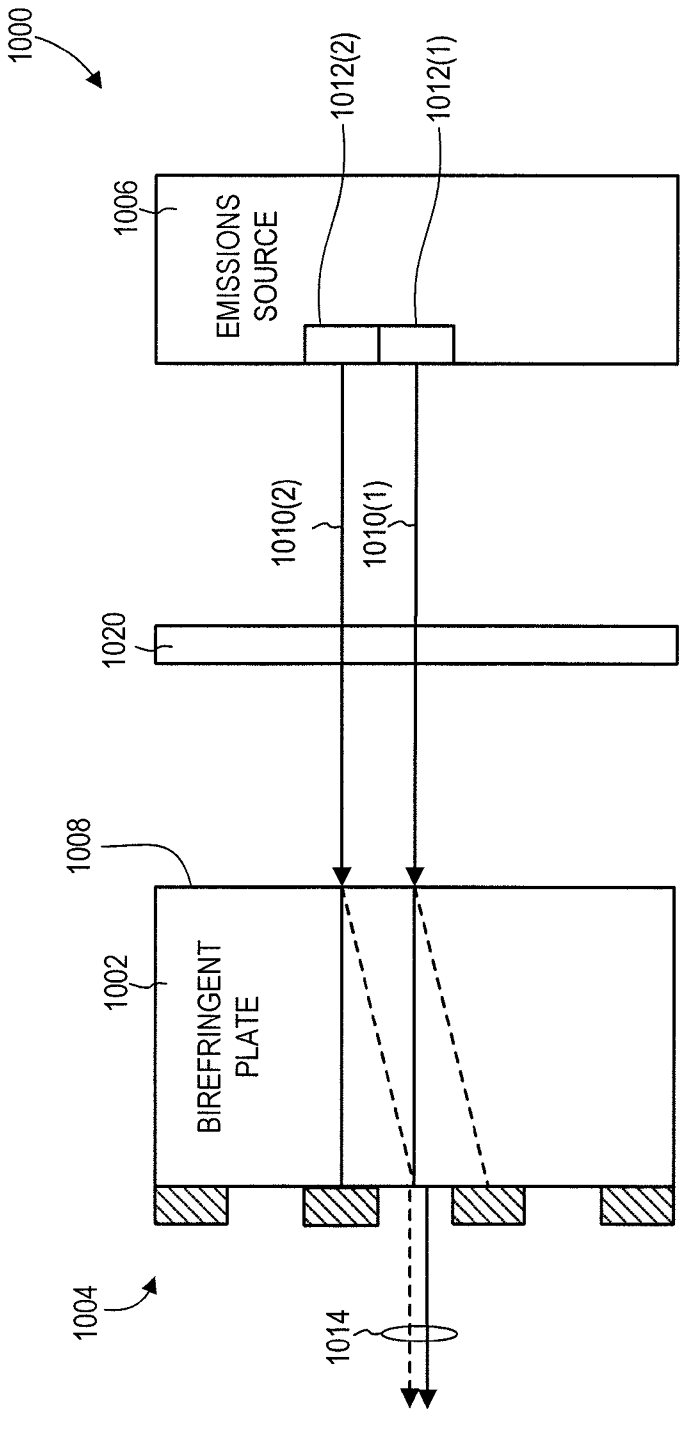
1000
1012(2)
1012(1)
1006
EMISSIONS SOURCE
1010(2)
1010(1)
1020
1008
1002
BIREFRINGENT PLATE
1004
1014

FIG. 10

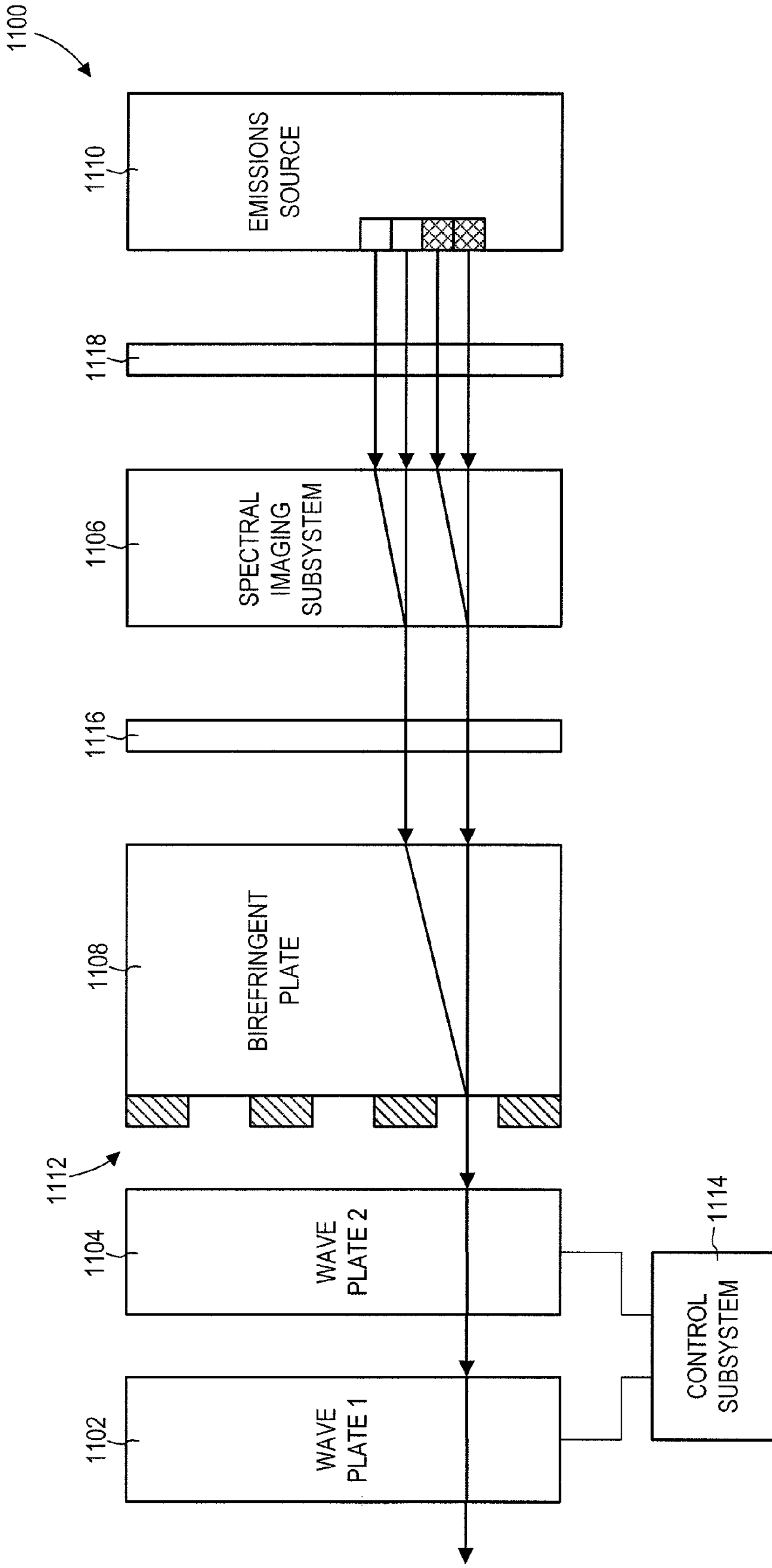
1100
1110
EMISSIONS SOURCE
1118
1106
SPECTRAL IMAGING SUBSYSTEM
1116
1108
BIREFRINGENT PLATE
1112
1104
WAVE PLATE 2
1102
WAVE PLATE 1
1114
CONTROL SUBSYSTEM

FIG. 11

OPTICAL SYSTEMS AND METHODS EMPLOYING A POLARIMETRIC OPTICAL FILTER

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of co-pending U.S. patent application Ser. No. 13/544,764, filed Jul. 9, 2012, which is a divisional of U.S. patent application Ser. No. 12/467,167, filed May 15, 2009, which claims benefit of priority to U.S. Provisional Patent Application No. 61/053,607, filed May 15, 2008, and to U.S. Provisional Patent Application No. 61/150,610, filed Feb. 6, 2009. Each of the above identified patent applications is incorporated herein by reference.

BACKGROUND

Passive imaging is a key technique for target detection, discrimination, and classification. Advances in imaging, spectral analysis, and active ranging now exploit larger regions of the electromagnetic spectrum from the ultraviolet ("UV") region to the very long wave infrared ("VLWIR") region to identify and separate targets from backgrounds and decoys. Existing imaging systems may detect electromagnetic wavelength, phase front, and time-of-flight to extract signatures of targets. However, one electromagnetic wave physical property that is not being fully exploited using existing technology is wave polarization state. Polarimetry, which is the measurement and interpretation of the polarization of electromagnetic waves, has potential applications such as target discrimination, buried mine detection, hidden object detection, measurement of sugar content in foods, purity measurement of pharmaceutical materials, and measurement of blood glucose.

Polarization of an electromagnetic wave can be characterized using a polarimetric imager. One existing polarimetric imager uses a polarizing beam-splitter and two cameras. Such imager suffers from the expense and space required to provide two cameras and the difficulty in spatially and temporally registering or aligning images from the two cameras. This imager also does not measure circular polarization.

Another existing polarimetric imager uses a rotating linear polarizer to acquire successive images at different polarizations. However, this imager requires significant time to scan the various polarizations, which may result in generation of artifacts due to motion of the target or camera, even from a leaf blowing in the wind.

A more recently developed polarimetric imager uses a "micropolarizer array". This imager measures four separate linear polarizations (0°, 90°, +45°, −45° on adjacent pixels, which are not coincident, and also reduces spatial resolution by four to one. Additionally, it may be difficult to align this imager with its focal plane array. Furthermore, this imager does not measure circular polarization.

SUMMARY

In an embodiment, a birefringent filter for separating rays of light incident thereon into ordinary rays and extraordinary rays includes a birefringent plate formed of a birefringent material. The filter further includes an EM directing element in optical alignment with a first surface of the birefringent plate.

In an embodiment, a polarimetric imager for simultaneously generating two orthogonally polarized images of a scene includes a birefringent filter for separating rays of light from the scene into ordinary rays and extraordinary rays. The filter includes a birefringent plate formed of a birefringent material and an EM directing element in optical alignment with a first surface of the birefringent plate. The imager further includes a detector in optical alignment with a second surface of the birefringent plate, for simultaneously generating a first image of the scene from the ordinary rays and a second image of the scene from the extraordinary rays.

In an embodiment, a projection system includes an electromagnetic energy emissions source and a birefringent filter. The filter includes (1) a birefringent plate formed of a birefringent material and having a first surface in optical alignment with the emissions source, and (2) an EM directing element in optical alignment with a second surface of the birefringent plate.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows one birefringent filter, according to an embodiment.

FIG. **1**A shows a front plan view of an opaque structure of the filter of FIG. **1**.

FIG. **2** shows one embodiment of the filter of FIG. **1**.

FIG. **2**A shows a front plan view of a Ronchi ruling of the filter of FIG. **2**.

FIG. **3** shows another embodiment of the filter of FIG. **1**.

FIG. **4** shows one polarimetric imager, according to an embodiment.

FIG. **5** shows one embodiment of the polarimetric imager of FIG. **4**.

FIG. **6** shows an alternative embodiment of the polarimetric imager of FIG. **5**.

FIG. **7** shows another alternative embodiment of the polarimetric imager of FIG. **5**.

FIG. **8** shows another alternative embodiment of the polarimetric imager of FIG. **5**.

FIG. **9** shows an embodiment of the polarimetric imager of FIG. **4** including a spectral imaging subsystem.

FIG. **9**A shows an imaging system including a hyperspectral imaging subsystem, according to an embodiment.

FIG. **9**B shows another imaging system including a hyperspectral imaging subsystem, according to an embodiment.

FIG. **9**C shows a polarimetric imager like that of FIG. **5**, but where the optical relay further includes a dispersive element, according to an embodiment

FIG. **10** shows one projection system, according to an embodiment.

FIG. **11** shows one embodiment of the projection system of FIG. **10**.

DETAILED DESCRIPTION OF THE EMBODIMENTS

It is noted that, for purposes of illustrative clarity, certain elements in the drawings may not be drawn to scale. Specific instances of an item may be referred to by use of a numeral in parentheses (e.g., slit **318**(**1**)) while numerals without parentheses refer to any such item (e.g., slits **318**).

FIG. **1** shows one birefringent filter **100** including a birefringent plate **108** and an electromagnetic energy ("EM") directing element, such as an opaque structure **112** as shown in FIG. **1**, in optical alignment with a surface **110** of plate **108**. Although FIG. **1** shows opaque structure **112** displaced from birefringent plate **108**, these two elements could be combined (e.g., laminated together). Opaque structure **112** includes a plurality of apertures **118** (only one is shown in FIG. **1** for illustrative clarity) allowing rays **102** to reach surface **110**.

Although filter **100** is generally described herein as including opaque structure **112** as an EM directing element, another EM directing element could supplement and/or replace opaque structure **112**. For example, a lens array could be used as an EM directing element in place of, or in addition to, opaque structure **112**.

Birefringent plate **108** is formed of a birefringent material. Birefringence is a property of certain materials where two polarization states have different indexes of refraction, ordinary and extraordinary. The ordinary index of refraction follow Snell's law of refraction while the extraordinary index of refraction does not. These birefringent material properties cause an orthogonally polarized optical ray traveling therethrough to split into two polarization states and refract at different angles. Accordingly, plate **108** separates incident rays of light **102** into ordinary rays **104** (s-polarization, polarized in a plane perpendicular to the plane of the page) and extraordinary rays **106** (p-polarization, polarized in the plane of the page). Ordinary rays **104** and extraordinary rays **106** may be re-imaged via a lens system (not shown) onto a focal plane **114**, which, for example, includes a detector, photographic film, or a projection screen. Birefringent plate **108** could optionally be formed of two birefringent plates laminated together to create a Savart plate, which has twice the deviation properties of a single birefringent plate.

The resulting image on focal plane **114** includes sets of image pairs, where each image pair has passed through the same aperture in opaque structure **112**. One of the images of a pair is p-polarized, while the other image of the pair is s-polarized. Thus, filter **100** advantageously can be used to create two orthogonally polarized images on focal plane **114**. Opaque structure **112** serves to space apart rays **102** incident on surface **110** to prevent image pairs from overlapping, thereby permitting interlacing. If opaque structure **112** were not present, an ordinary ray **104** might overlap an adjacent extraordinary ray **106** on focal plane **114**. Accordingly, apertures **118** of opaque structure **112** have, for example, a spacing at least as great as a separation **116** (after magnification) between a pair of ordinary and extraordinary rays emerging from birefringent plate **108**. A lens array or other EM directing element could optionally be used in place of opaque structure **112** to separate rays **102** incident on surface **110**. Furthermore, in one embodiment, filter **100** does not have opaque structure **112** or any other EM directing element at all; removal of overlap from focal plane **114** is instead accomplished via image processing techniques.

Opaque structure **112**'s plurality of apertures **118** includes, for example, a pinhole array, such as shown in FIG. **1**A, which shows a front plan view of opaque structure **112**. However, opaque structure **112** and/or plurality of apertures **118** may have other configurations. For example, opaque structure **112** could have a shape other than rectangular (e.g., circular). As another example, plurality of apertures **118** may include a random array of apertures or a Ronchi ruling, such as shown in FIG. **2**, which is a cross sectional view of a birefringent filter **200**. Filter **200**, which is an embodiment of birefringent filter **100** (FIG. **1**), includes a birefringent plate **208** and an opaque structure including a Ronchi ruling **212** disposed on a surface **210** of plate **208**. Ronchi ruling **212** is, for example, disposed orthogonal to a birefringence refraction plane of birefringent plate **208**. Ronchi ruling **212** could alternately be displaced from surface **210**.

FIG. **2**A shows a front plan view of Ronchi ruling **212**. Ronchi ruling **212** includes an alternating pattern of opaque lines **218** and clear apertures or slits **214**. Ronchi ruling **212** is, for example, formed of chrome on glass and has a 50% duty cycle of opaque lines **218** and slits **214**. The duty cycle and thickness of the birefringent plate **208** may be adjusted to minimize crosstalk. It may be advantageous for separation **216** between exiting rays **204** and **206** to equal the pitch of Ronchi ruling **212** to allow the image to completely fill a focal plane **214** without dead bands. As shown in FIG. **2**, ray a **202** incident on a slit **214** in Ronchi ruling **212** is separated into an ordinary ray **204** and an extraordinary ray **206**.

Examples of the birefringent material of plate **108** include calcite, quartz, zinc selenide, cadmium sulfide, and cadmium selenide. Calcite may be particularly suited for visible light applications or for 0.13 μm ultraviolet through 2.1 μm short wave infrared applications. For example, a 0.46 mm thick birefringent plate may produce a separation between an ordinary/extraordinary line pair of 50 μm, and may be paired with a Ronchi ruling have 50 μm slits. Cadmium sulfide may be particularly suited for infrared light applications. For example, a 0.9 mm thick cadmium sulfide birefringent plate may also produce a separation between an ordinary/extraordinary line pair of 50 μm.

Opaque structure **112** (FIG. **1**) blocks light and thereby reduces the throughput of filter **100**. In particular, only light that is incident on an aperture in opaque structure **112** passes through birefringent filter **100**. This throughput reduction can be addressed by imaging additional frames on focal plane **114**. Alternately or additionally, optics, such as an array of lenslets, may be disposed on opaque structure **112**. For example, FIG. **3** shows a cross-sectional view of birefringent filter **300**, which is an embodiment of filter **100**. Birefringent filter **300** includes a birefringent plate **308** and a Ronchi ruling **312** formed on a surface **310** of plate **308**. A lenslet array **314** is disposed on Ronchi ruling **312**.

Lenslet array **314** includes a cylindrical lens or lenslet **316** for each slit **318** of Ronchi ruling **312**. As shown in FIG. **3**, lenslets **316** help capture incident rays **302** that would not otherwise be incident on a slit **318**. Lenslets **316**, for example, funnel photons down to a half of the number of pixels used to capture the orthogonal polarization on a neighboring rows of pixels of a detector at a focal plane. At visible and near infrared wavelengths, lenslets **316** may be fabricated by molding or embossing plastic or glass. For example, lenslets **316** may be molded or embossed into a single side of a sheet of plastic. At infrared wavelengths, lenslets **316** are, for example, molded of chalcogenide glass or etched into silicon or germanium. Lenslets **316** may also be fabricated as a fresnel lens.

As discussed above, filter **100** can include a lens array, or other EM directing element, in place of, or in addition to, opaque structure **112**. Accordingly, filter **300** could be modified to remove Ronchi ruling **312**.

FIG. **4** shows one polarimetric imager **400** including an embodiment of filter **100** and a detector **418** at a focal plane **430**. Specifically, imager **400** includes a birefringent plate **408**, an opaque structure **412**, and detector **418** in optical alignment with a second side **420** of birefringent plate **408**. Examples of detector **418** include a charge coupled device (CCD) detector and a complimentary metal oxide semiconductor (CMOS) detector. Imager **400** optionally includes processing subsystem **428** communicatively coupled to detector **418** for processing data generated by detector **418**. Although opaque structure **412** is shown as including a Ronchi ruling, opaque structure **412** could have another configuration, such as pinhole array or a Ronchi ruling including a lenslet array. Additionally, in some embodiments of imager **400**, opaque structure **412** is omitted and processing subsystem **428** separates overlapping images generated by detector **418**. Furthermore, opaque structure **412** could be replaced with, or supplemented with, another EM directing element, such as a lens array.

The filter of imager **400** optionally includes a first wave plate **414** and a second wave plate **416**. Each of wave plates **414**, **416** may be variable wave plates, such as shown in FIG. **4**. However, at least one of wave plates **414**, **416** could be a fixed wave plate, such as a circular wave plate. Embodiments including one or more variable wave plates optionally include a control subsystem **426** communicatively coupled with and controlling the wave plates, such as shown in FIG. **4**. Although control subsystem **426** and processing subsystem **428** are shown as separate subsystems, they may be embodied by a single subsystem, such as a computer controlling imager **400**.

Imager **400** is operable to simultaneously generate two orthogonally polarized images from a scene **432**. In particular, if wave plates **414**, **416** are not present, the birefringent filter separates incoming rays **402** from scene **432** into respective ordinary rays **404** (p-polarization) and extraordinary rays **406** (s-polarization). Ordinary rays **404** impinge pixels **422** to form a first image, and extraordinary rays **406** impinge pixels **424** to form a second image on detector **418**. The first and second images are thus interlaced on detector **418** and are advantageously permanently aligned, thereby minimizing co-registration issues. The first and second images may also be simultaneously read-out to eliminate temporal distortions. To limit crosstalk to a fraction of a percent or less at the expense of image pixel count, a buffer band of pixels can be included in detector **418** between polarization lines of data (e.g., between pairs of pixels **422**, **424**). Although FIG. **4** shows a number of incoming rays **402**, imager could be used in applications where scene **432** emits a single ray **402**.

Accordingly, imager **400** can advantageously collect electronic images and electromagnetic information at different polarizations simultaneously on a single two-dimensional (2D) focal plane array (i.e., detector **418**) without scanning or moving parts. Thus, imager **400** may be cheaper, smaller, lighter, and/or more reliable than other polarimetric imagers. The filter (i.e., birefringent plate **408** and opaque structure **412** and/or another EM directing element) can advantageously be permanently aligned with detector **418**. A three- (or four-) dimensional data cube, x, y, p_1, and p_2 (representing orthogonal polarization states) may be simultaneously collected and optionally processed by processing subsystem **428**. Imager **400** is not limited to visible light applications. Imager **400**, for example, can be used in wave bands for which 2D detectors are available, including UV, visible, near infrared ("NIR"), mid-wave infrared ("MWIR"), long-wave infrared ("LWIR"), and millimeter wave band ("MMW") wave bands.

Incoming rays, such as from scene **432**, may be partially polarized, as well as linearly or circularly polarized. The Stokes vector, S, may be used to describe partially polarized light in terms of its total intensity. As is known in the art, the Stokes vector includes elements S_0, S_1, S_2, and S_3, which can be computed as follows.

$$S_0=I_0+I_{90} \tag{1}$$

$$S_1=I_0-I_{90} \tag{2}$$

$$S_2=I_{45}-I_{-45} \tag{3}$$

$$S_3=I_L-I_R \tag{4}$$

I_0 and I_{90} are the linear polarization intensities in an orthogonal coordinate system, I_{45} and I_{-45} are the linear polarization intensities along axes that are rotated by 45° with respect to the original coordinate system, and I_L and I_R are the intensities of the left and right circular polarization components of the light beam, respectively. Accordingly, the entire Stokes vector can be determined from I_0, I_{90}, I_{45}, I_{-45}, I_L, and I_R.

The first and second images generated by detector **418** without wave plates **414** and **416** present respectively correspond to I_0 and I_{90}. Optional wave plates **414**, **416** enable imager **400** to additionally generate first and second images respectively corresponding to I_{45} and I_{-45}, and/or I_L and I_R. Wave plates **414**, **416** are, for example, variable wave plates operable to phase shift rays passing therethrough in accordance with a control signal, such as an electrical control signal from control subsystem **426**. For example, wave plates **414**, **416** may each be an electrically controlled liquid crystal rotator that allows light to pass therethrough without phase shift when an electrical signal is applied and that acts as a quarter wave plate when no electrical control signal is applied. Other examples of wave plates **414**, **416** include electro-optic rotators, kerr cells, and pockels cells.

In the example of FIG. **4**, wave plate **414** is disposed such that it is in optical alignment with opaque structure **412**. Second wave plate **416** is disposed between and in optical alignment with first variable wave plate **414** and opaque structure **412**. First wave plate **412**, for example, has a vertically aligned fast axis, and second wave plate **416** has a fast axis that is angularly displaced by forty five degrees from the fast axis of first wave plate **414**.

Wave plates **414**, **416** are, for example, variable wave plates that are independently controlled by control subsystem **426**. For example, control subsystem **426** can provide signals (e.g., electrical signals) independently switching wave plates **414**, **416** between a zero phase shift operating mode and quarter wave plate operating mode. As another example, control subsystem **426** may be operable to adjust variable wave plates **414**, **416** to maximize polarization contrast of the first or second images generated by detector **418**.

TABLE 1 below summarizes three different combinations of operating modes of an embodiment including wave plates **414**, **416** that are variable wave plates. In operating mode 1, both wave plates **414**, **416** are operated such that they introduce no phase shift. Accordingly, detector **418** forms first and second images respectively corresponding to I_0 and I_{90}. In operating mode 2, both wave plates **414**, **416** act as quarter wave plates, and detector **418** forms first and second images respectively corresponding to I_{45}, and I_{-45}. In operating mode 3, first wave plate **414** does not introduce phase shift while second wave plate acts a quarter wave plate. In operating mode 3, detector **418** forms first and second images respectively corresponding to I_L, and I_R. TABLE 1 only summarizes some possible operating modes of an embodiment of imager **400**—other operating modes are possible.

TABLE 1

Operating Mode	1^{st} Wave Plate	2^{nd} Wave Plate	Measured at detector
1	no phase shift	no phase shift	I_0 and I_{90}
2	quarter wave	quarter wave	I_{45} and I_{-45}
3	no phase shift	quarter wave	I_L and I_R

Accordingly, an embodiment of imager **400** can be operated, such as by control subsystem **426**, to generates sets of first and second images at each of operating modes 1-3. For example, the embodiment of imager **400** can be operated in each of modes 1, 2, and 3 to generate a set of images corresponding to (1) I_0 and I_{90}, (2) I_{45} and I_{-45}, and (3) I_L and I_R. Thus, embodiments of imager **400** including variable wave plates **414**, **416** can be used to determine the entire Stokes vector by capturing just three image frames. Additionally, if it is expected that no circular polarized rays are to be emitted from the scene **432**, mode 3 can be eliminated and stokes vector component S_3 can assumed to be zero, thus reducing the frames needed to two.

Optional processing subsystem **428** is operable to process first and second images generated by detector **418**. Processing subsystem **428** may be implemented by a general purpose or specialized computer including a processor that executes instructions, such as in the form of software or firmware stored on a computer readable medium, to process images from detector **418**. Processing subsystem **428**, for example, digitally separates data from detector **418** to separate the first and second images. Processing subsystem **428** could, for example, subtract or ratio the first and second images to provide polarization discrimination information. As another example, processing subsystem **428** could be operable to sum the first and second images to yield intensity.

Processing subsystem **428**, for example, can display or analyze polarization data in an acceptable manner once first and second images are collected from detector **418**. For example, in human vision applications of imager **400**, the three Stokes vector parameters S_1, S_2, and S_3 may be represented as false colors. As another example, the degree of polarization, p, may be displayed as a false color superimposed on a monochrome display of S_0. Alternately, the polarization states of the image may be represented as points mapped on a Poincaré sphere.

Processing subsystem **428** is, for example, operable to process first and second images generated by detector **418** to determine at least some elements of the Stokes vector, S, or another polarization characterization system. For example, processing subsystem **428** may be operable to calculate the Stokes vector using equations (1)-(4) above with input data including pairs of first and second images generated from each of operating modes 1-3 of TABLE 1 above.

Some embodiments of processing subsystem **428** are advantageously operable to adjust or remove information from an image of scene **432** using polarization information from sets of first and second images generated by detector **418**. For example, in a forest scene, light emitted from a tree canopy may be non-polarized, and processing subsystem **428** may remove the tree canopy from an image of the forest scene by removing non-polarized portions of the image.

Some embodiments of processing subsystem **428** are also operable to identify a target in scene **432**. Polarization of objects is related to planar surfaces of the objects, and such planar surfaces can often indicate whether the objects are man-made. Accordingly, processing subsystem **428** could, for example, use polarization information to discriminate a man-made object from more natural clutter in scene **432**. As another example, processing subsystem **428** could be operable to detect illumination in a scene from a polarized laser source, as opposed to illumination from a natural, or other, light source.

Some embodiments of imager **400** can advantageously be integrated with an acceptable detector or focal plane array (FPA) without alteration to the FPA. Adjacent lines on the FPA may carry identical spatial information, but with different orthogonal polarizations. Some embodiments of imager **400** may also be: (i) used to form framing cameras that can run kHz rates; (ii) integrated into miniature cameras and/or disposable cameras; or (iii) used in infrared cameras.

Possible uses of some embodiments of imager **400** may include one or more of the following:

1. Identifying targets in clutter.
2. Identifying man-made objects, such as those camouflaged or those located in high-glare littoral (marine) environments.
3. Detecting buried landmines, such as by identifying man-made objects and/or disturbed soils.
4. Characterizing materials, including agricultural and food materials.
5. Enhancing contrast in biomedical and pharmaceutical applications, such as enhancing mammograms and other subsurface (soft) tissue images.
6. Locating laser light.
7. Replacing a polarizer analyzer pair conventionally used in microscopes to measure the polarization of samples under the microscope.
8. Measuring thin film thickness using ellipsometry.
9. Inspecting glass and glass bottles during manufacturing.
10. Measuring optical properties of a material, including linear birefringence, circular birefringence (also known as optical rotation or optical rotary dispersion), linear dichroism, circular dichroism, and scattering.
11. Measuring polarization of light from an external light source and reflected from or transmitted through a sample as well as the fluorescence, phosphorescence, or luminescence of light generated by a sample.

Advantages of some embodiments of the imager **400** may include one or more of the following:

1. Only one detector is required to obtain two polarization states.
2. Two polarization states may be simultaneously recorded on a single detector.
3. An entire Stokes vector can be recorded by using wave plates **414**, **416** before birefringent plate **408**.
4. Motion artifacts may be reduced or eliminated due to simultaneous generation of the first and second images.
5. Some embodiments of imager **400** operate in the infrared band, thereby minimizing the need for expensive infrared-band focal plane arrays.
6. Some embodiments of imager **400** can be mounted in a filter wheel and can be swung in and out of the image stream to interchange with other imaging systems.
7. As discussed below, some embodiments of imager **400** can be combined with a dispersive element (e.g., in a HyperPixel Array imager) to provide both polarimetric and spectral data in an image.
8. Some embodiments of imager **400** can be disposed adjacent to a detector without requiring a reimaging lens.
9. Some embodiments of imager **400** can be coupled to a detector using a short lens array or a grin lens array (Selfoc).
10. Some embodiments of imager **400** can be used in a projection system to project polarimetric scenes.
11. Some embodiments of imager **400** can incorporate a detector **418** smaller than a typical FPA array, such as a two- or three-pixel detector.
12. Some embodiments of imager **400** can be used to project polarized light and images in both linear and circular polarization states.
13. Some embodiments of imager **400** can be used to measure circularly polarized light.

FIG. **5** shows a side plan view of one imager **500**, which is an embodiment of imager **400** (FIG. **4**). Imager **500** includes a primary lens **502** (e.g., a camera lens, such as a Nikkor 50 MM F/1.4 lens as shown in FIG. **5**), a first variable wave plate **504**, a second variable wave plate **506**, a filter **508** (which is an embodiment of filter **100**, FIG. **1**), an optical relay **510**, and a detector **512**, which is, for example, a CCD or CMOS detector. Primary lens **502** can be interchanged with another lens to vary the field of view. Orthogonal polarization state images can be read out simultaneously from a single array of detector **512**. As discussed below, optical relay **510** can optionally be eliminated by coupling filter **508** directly to detector **512**, such as using a Selfoc lens array relay. (A Selfoc lens array is a GRIN lens image relay system developed for copying machines). Furthermore, filter **508** may be contact-coupled to detector **512**.

FIGS. **6-8** show several possible manners of integrating filter **508** with detector **512**. The embodiments shown in FIGS. **6-8** may advantageously be utilized to allow an assembly including filter **508** and detector **512** to be relatively compact.

FIG. **6** is a cross sectional view of filter **508** coupled to detector **512** using a Selfoc lens array relay **602**. FIG. **7** is a cross sectional view of filter **508** coupled to detector **512** using a double lenslet array relay **702**. A field lens **704** is optionally disposed in the middle of lenslet array **702**. FIG. **8** is a cross sectional view of filter **508** directly coupled to detector **512**.

Some embodiments of imager **400** are operable to detect spectral information in addition to polarization and intensity information. For example, FIG. **9** shows one imaging system **900**, which is an embodiment of imaging system **400** including spectral imaging subsystem **902**. Spectral imaging subsystem **902** is operable to separate ordinary and extraordinary arrays emerging from surface **904** of birefringent plate **906** according to their spectral content. Accordingly, detector **908**, which is, for example, angularly displaced by 90 degrees from the direction of dispersion of spectral imaging subsystem **902**, forms a plurality of images that represent both polarization and spectral characteristics of rays **910** emitted from the scene. Spectral imaging subsystem **902**, for example, includes a dispersive element such as a prism, or is a hyperspectral imaging subsystem, such as disclosed in U.S. Patent Application Publication No. 2008/0088840 to Bodkin et al., which is incorporated herein by reference.

For example, FIG. **9**A shows an imaging system **922**, which is one possible implementation of imaging system **900** including a hyperspectral imaging subsystem. Imaging system **922** includes a collimating lens **924**, a dispersive element **926**, and a focusing lens **928**. Collimating lens **924** is in optical alignment with birefringent plate surface **904** and collimates ordinary and extraordinary rays emerging from surface **904** into collimated rays **930**. The ordinary and extraordinary rays emerging from surface **904** are collectively shown as rays **932** in FIG. **9**A to promote illustrative clarity. Dispersive element **926** is in optical alignment with collimating lens **924** and separates collimated rays **930** into spectrally separated rays **934** according to their spectral content. Dispersive element **926** includes, for example, a prism. Focusing lens **928** is in optical alignment with both dispersive element **926** and detector **908**, and focusing lens **928** focuses spectrally separated rays **934** onto detector **908**.

As another example, FIG. **9**B shows an imaging system **936**, which is like imaging system **922** of FIG. **9**A, but with opaque structure **920** replaced with lenslet array **938** disposed on an aperture array **940**. As yet another example, FIG. **9**C shows an imaging subsystem **942**, which is like imager **500** of FIG. **5**, but where optical relay **510** further includes a dispersive element **944**.

The configuration of imager **900** can be varied from the example of FIG. **9**. For example, wave plates **912**, **914**, control subsystem **916**, and/or processing subsystem **918** could be omitted. Also, at least one of wave plates **912**, **914** could be a fixed wave plate instead of a variable wave plate. Furthermore, although opaque structure **920** is shown as including a Ronchi ruling, opaque structure **920** could have another configuration (e.g., could include a pinhole array, a lenslet array on a Ronchi ruling, or a hardware coded aperture array). Opaque structure **920** could be replaced with, or supplemented with, another EM directing element, such as a lens array.

Embodiments of filter **100** can also be used to filter polarization information from an electromagnetic energy emissions source, such as for use in projecting photons having certain polarization. For example, projection system **1000** of FIG. **10** includes a birefringent plate **1002**, an opaque structure **1004** (e.g., a Ronchi ruling as shown in FIG. **10**), and an electromagnetic emissions source **1006** in optical alignment with a surface **1008** of plate **1002**. Emissions source **1006** is, for example, a light source, an infrared energy source, or a mid wave band energy source. Opaque structure **1004** could be replaced with, or supplemented with, another EM directing element, such as a lens array. Imaging system **1100** may also include one more additional optics, such as a lens **1020**.

Emissions source **1006** is, for example, a light source such as a liquid crystal array with its polarizers rotated at 45 degrees with respect to a plane of birefringent plate **1002**, one or more light emitting diodes, or a polarized light source. In the example of FIG. **10**, projection system **1000** filters rays **1010** from pixels **1012** of emissions source **1006** such that only s-polarized rays **1014** emerge from opaque structure **1004**. According, in the example of FIG. **10**, projection system **1000** projects s-polarized rays **1014**. However, other embodiments of imaging system **1000** project p-polarized rays. Although emissions source **1006** is shown as including a plurality of pixels **1012**, emissions source **1006** could be a single pixel source.

Projection system **1000** optionally further includes one or more wave plates and/or a spectral imaging subsystem. The wave plates allow further control of polarization of rays projected from system **1000**. For example, a wave plate could be used to converter linear polarized rays into circularly polarized rays. The spectral imaging subsystem separates electromagnetic energy from emissions source **1006** according to wavelength and thereby allows control of the spectral content of rays projected from system **1000**.

For example, FIG. **11** shows one projection system **1100**, which is an embodiment of imaging system **1000** including a first wave plate **1102**, a second wave plate **1104**, and a spectral imaging subsystem **1106** (e.g., including a dispersive element such as a prism) disposed between and in optical alignment with a birefringent plate **1108** and an electromagnetic energy emissions source **1110**. Emissions source **1110** is angularly displaced from the direction of dispersion of spectral imaging subsystem **1106** by 90 degrees, for example. First wave plate **1102** is in optical alignment with an opaque structure **1112**. Second wave plate **1104** is disposed between and in optical alignment with first wave plate **1102** and opaque structure **1112**. Wave plates **1102**, **1104** are, for example, variable wave plates controlled by optional control subsystem **1114**. In such embodiments, control subsystem **1114** may be operable to adjust the operating modes of wave plates **1102**, **1104** to optimize an image projected by system **1100**. Projection system **1100**, for example, includes additional optics, such as lenses **1116**, **1118**. Additionally, opaque structure **1112** could be replaced with, or supplemented with, another EM directing element, such as a lens array.

Some embodiments of projection system **1000** (FIG. **10**) could be used as a three dimension projector to interlace a stereoscopic pair onto a projection screen. For example, emissions source **1006** could be a single projector, and a viewer could wear polarized glasses (e.g., including a p-polarized lens and an s-polarized lens) and view a three dimensional image from exiting rays **1014**. Such system would advantageously only require a single projector, in contrast to some other three dimensional projection systems that require at least two projectors.

Changes may be made in the above methods and systems without departing from the scope hereof. It should thus be noted that the matter contained in the above description and shown in the accompanying drawings should be interpreted as illustrative and not in a limiting sense. The following claims are intended to cover generic and specific features described herein, as well as all statements of the scope of the present method and system, which, as a matter of language, might be said to fall therebetween.

What is claimed is:

1. A polarimetric imager, comprising:

an optic for creating an image of a scene;

an aperture array for separating rays of light originating from a plurality of different portions of the image of the scene into a respective plurality of spatially separated ray bundles;

a birefringent plate for separating each of the plurality of spatially separated ray bundles into ordinary rays and extraordinary rays;

a spectral imaging subsystem for separating the ordinary and extraordinary rays according to their spectral content; and

a detector array for generating data from the ordinary and extraordinary rays separated according to their spectral content.

2. The polarimetric imager of claim **1**, further comprising a processing subsystem communicatively coupled to the detector array for generating a data cube from the data generated by the detector.

3. The polarimetric imager of claim **1**, the data comprising polarimetric data, spectral data, and spatial data, from the image of the scene.

4. The polarimetric imager of claim **1**, the spectral imaging subsystem comprising a dispersive element.

5. The polarimetric imager of claim **4**, the dispersive element comprising a prism.

6. The polarimetric imager of claim **1**, the spectral imaging subsystem comprising a hyperspectral imaging subsystem.

7. The polarimetric imager of claim **6**, the hyperspectral imaging subsystem comprising:

a collimating lens in optical alignment with the birefringent plate;

a dispersive element for receiving light from the collimating lens, the dispersive element being in optical alignment with the collimating lens; and

a focusing lens for receiving light from the dispersive element, the focusing lens being in optical alignment with the dispersive element and the detector array.

8. The polarimetric imager of claim **7**, the dispersive element comprising a prism.

9. The polarimetric imager of claim **7**, the aperture array comprising a pinhole array.

10. The polarimetric imager of claim **7**, the aperture array comprising lenslet array.

11. The polarimetric imager of claim **7**, further comprising at least one wave plate in optical alignment with the aperture array.

12. The polarimetric imager of claim **11**, the wave plate comprising two variable wave plates, the imager further comprising a control subsystem operable to independently adjust an operating mode of each of the variable wave plates to maximize polarization contrast in the data.

13. The polarimetric imager of claim **11**, further comprising a control subsystem operable to control the wave plate.

14. The polarimetric imager of claim **13**, further comprising a processing subsystem communicatively coupled to the detector array and operable to calculate polarization characteristics describing polarization of the image of the scene from data generated by the detector array at different operating modes of the wave plate.

15. The polarimetric imager of claim **14**, the processing subsystem operable to clarify information from the image of the scene according to polarization information from the data generated by the detector array at different operating modes of the wave plate.

16. The polarimetric imager of claim **14**, the processing subsystem operable to identify a target of interest in the image of the scene from the data generated by the detector at different operating modes of the wave plate.

17. A polarimetric imager, comprising:

an optic for creating an image of a scene;

a lenslet array for separating rays of light originating from a plurality of different portions of the image of the scene into a respective plurality of spatially separated ray bundles;

a birefringent plate for separating each of the plurality of spatially separated ray bundles into ordinary rays and extraordinary rays;

a spectral imaging subsystem for separating the ordinary and extraordinary rays according to their spectral content; and

a detector array for generating data from the ordinary and extraordinary rays separated according to their spectral content.

18. The polarimetric imager of claim **17**, the spectral imaging subsystem comprising:

a collimating lens in optical alignment with the birefringent plate;

a dispersive element for receiving light from the collimating lens, the dispersive element being in optical alignment with the collimating lens; and

a focusing lens for receiving light from the dispersive element, the focusing lens being in optical alignment with the dispersive element and the detector array.

19. A method for simultaneously generating polarimetric image data, spectral image data, and spatial image data, from an image of a scene, comprising the steps of:

separating rays of light originating from a plurality of different portions of the image of the scene into a respective plurality of spatially separated ray bundles;

separating each of the plurality of spatially separated ray bundles into ordinary rays and extraordinary rays;

collimating the ordinary and extraordinary rays into collimated rays; and

separating each of the collimated rays into a plurality of spectrally separated rays according to their spectral content.

20. The method of claim **19**, the step of separating the collimated rays comprising using at least one prism to separate the collimated rays according to their spectral content.

21. The method of claim **19**, further comprising:

focusing the spectrally separated rays onto a detector array; and generating a data cube from data generated by the detector array.

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